

Some Comments on the Putative Θ^+ (1543) Exotic State

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We point out that existing K^+d scattering data available in the PDG (Particle Data Group compilation) suggest some fluctuations in those momentum bins where the (Fermi motion broadened) $\Theta^+[1543]$ resonance recently indicated in many gamma nuclear reactions and predicted six years ago by Diakonv Petrov and Polyakov might have shown up. The $I = 0$, $J^P = \frac{1}{2}^+$ P-wave channel should have a universal peak cross section of ~ 37 mb at resonance. The smallness of the effect seen in K^+d with the $\delta\sigma$ fluctuations being less than 4 mb imply an indirect bound $\Gamma_{\Theta^+} < 6$ MeV, far stronger than the direct gamma-d measurements. This renders the theoretical interpretation of the new state very difficult.

I. INTRODUCTION

Indications for a K^+n resonance at a mass of 1543 MeV were found in several Photon deuteron collision experiments [1, 2] the final K^+K^-pn state and also in $K^+ - Xe$ collisions[3] suggest that a low-lying narrow 5-quark $\bar{s}uudd$ state, the Z^+ exists. Capstick, Page and Roberts (CPR) [4] suggested that Z^+ is an isotensor. Such a state can be produced in $\gamma + d \rightarrow nK^+K^-p$ reactions but decays slowly into $I = 0$ or $I = 1$ final KN states due to the I-spin violation required, explaining the narrow width.

In a remarkable 1997 paper, Diakonov, Petrov and Polyakov (DPP)[5] started with an SU(3) extension[6] of the Skyrme model and predicted a low-lying SU(3) $\overline{10}$ anti-decuplet of $\frac{1}{2}^+$ baryons with $\Theta^+ = \bar{s}uudd$ serving as its $I = 0$ lowest hypercharge and lowest mass

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entry. Identifying the $I = 1/2$ doublet in this antidecuplet with the N(1710) state they predicted $m_{\Theta^+} \sim 1530$ MeV, close to the experimental 1543 MeV value. Having $I = 0$ it can appear in K^+n and K^0p but not in the well studied K^+p channel, which indeed has no resonances! Also DPP estimated a width $\Gamma_{\Theta^+} \simeq 15 \text{ MeV}$, consistent with the present direct experimental upper bounds $\Gamma < 20$ MeV. Unfortunately, the starting point of DPP, namely the baryonic soliton in large N_c and chiral SU(3), makes the paper somewhat inaccessible.

In the following we present naive quark model (NQM) arguments, which explain in simple terms why the $\bar{s}uudd$, $I = 0$, $J^P = \frac{1}{2}^+$ state is likely to be low-lying. The argument clarifies connections to earlier Bag-NQM predictions of Hexa-[8], Penta-[9, 10] and Tetra-quarks[11, 12]. It also implies that $I(\Theta^+) = 2$, the simplest explanation for the narrow width, is extremely unlikely.

Our main observation which we present next is that the *lack* of a prominent Θ^+ signature in $K^+ - d$ collisions restricts the width to $\Gamma_{\Theta^+} < 6$ MeV making $I(\Theta^+) = 0$ barely consistent even in the special context of DPP's anti-decuplet.

II. BOUNDS ON THE Θ^+ WIDTH

We use the following simple observations:

- (i) The $l = 1$ orbital angular momentum of the K-N Θ^+ resonance predicted by DPP is almost model-independent: In $l = 0$ the attractive nuclear forces cannot yield narrow resonances but only threshold enhancements as in S-wave N-N scattering and $l > 1$ is unlikely for the low-lying Θ^+ .
- (ii) The general expression for the total $K^+ - n$ cross section is:

$$\sigma_{K^+n}(p) = \frac{4\pi}{p^2} \Sigma_l (2l+1) E \sin^2 \delta_l(p) \quad (1)$$

with p the momentum of K or n in the center of mass Lorentz frame, and $E = E(I, J)$ reflects the I spin and angular momentum projection "Clebsches". The resonant phase shift is $\delta_l(p) = \pi/2$ and the relevant partial wave cross section saturates at a universal value. For the Θ^+ with $p = 0.27$ GeV and $l = 1$ the value is:

$$\sigma_{\Theta^+}|_{res} \simeq \frac{4\pi}{p^2} \cdot 3 \cdot \left(\frac{1}{2}\right) \cdot \left(\frac{1}{3}\right) \simeq 37 \text{ mb} \quad (2)$$

The factor $1/2$ reflects the equal-magnitude projections of the $A(K^+ - n)$ and $A(K^0 - p)$ scattering amplitudes on the $I = 0$ resonant amplitude and the $I = 1$ non-resonant

amplitudes (implying also equal elastic $K^+n \rightarrow K^+n$ and charge exchange (CEX) $K^+n \rightarrow K^0 + p$ parts). The second factor of $1/3$ is the probability that the $l = 1$ orbital and $s = 1/2$ spin of the nucleon add up to the desired $J = 1/2$.

(iii) The implications of the universal resonant cross section in specific cases depend on the width of the relevant state. Thus the minute neutrino electron $\bar{\nu}_e - e$ cross section jumps by ~ 10 orders of magnitude at the π^- mass. However, the tiny width $\Gamma_{\pi^-} \sim 10^{-17}$ GeV makes this unobservable.

Let the width of the putative new resonanc be $\Gamma_{\Theta^+} = g \ 20\text{MeV}$. The 20 MeV "reference" value predicted by DPP, is consistent with direct observations. If neutron targets and/or monochromatic K^0 beams were available the Θ^+ would manifest as a threefold increase in the $K - N$ cross section if Γ_{Θ^+} exceeds the step size in the scan. In reality neither is available. However, as we show in the next section, existing K^+ -deuteron data indirectly exclude widths larger than ~ 6 MeV.

(iv) The KN channels have been extensively studied in the 60's using , in particular, bubble chambers. The absence of resonances in K^+p , dramatically contrasted the resonances or $\bar{K}N$ "bound states" (decaying to $\Lambda + \pi$) found in K^-p scattering.

The PDG[13] plots of K^-N cross sections indicate, for CMS energies below $m_{\Theta^+} = 1540$ MeV huge $O(80)$ mb cross sections, which , as expected for the exothermic process, blow up like $1/v$ towards threshold.

Using K^0 beams (obtained by K^+ CEX reactions) to search for the Θ^+ in K^0p reactions in Hydrogen bubble chambers is inherently impossible. Despite some material, "index of refraction" effects, the propagating states are, as in vacuum, almost an equal mixture of K_{short} and K_{long} with the mildly relativistic K_S 's decaying into two pions along paths of order 1-2 cm, shorter than the mean free paths for K-N interactions. The remaining K_L 's are an equal mixture of K^0 and \bar{K}^0 , and the huge cross section of the \bar{K}^0 components can mask the fine structure in the $K^0 - p$ cross section which is being searched.

This does not hinder (and even helps!) searching the Θ^+ in K^+d data. The total K^+d cross section reflects the Θ^+ resonance in the K^+n channel albeit broadened by the neutrons' Fermi motion. To estimate the latter we use a Yukawa $\exp -\mu r/r$ deuterons' wave function with:

$$\mu = \sqrt{m(N).BE} \sim 50\text{MeV} . \quad (3)$$

The probability $P(k)$ that the neutron has a "Fermi" momentum k is the square of the

Fourier transform of the wave function

$$P(k) \propto \frac{1}{(\mu^2 + k^2)^2}. \quad (4)$$

If the lab momentum of the K^+ in the rest frame of the deuteron is q , then for any given $|k|$ the “lab” momentum for the K^+n collision of interest is uniformly distributed in the $(q - |k|, q + |k|)$ interval. This broadens the putative Θ^+ resonance plotted versus the K^+d lab momentum by $\Delta q = 2\mu$, i.e. by 100 MeV. The mapping of $W(\text{cm})$ to q -lab momentum in the vicinity of $W = m_{\Theta^+} = 1543$ MeV doubles the original $\Gamma_{\Theta^+} = g$ 20 MeV to g 40 MeV in the q variable. Fermi motion broadens this into $(g \ 40 + 100)$ MeV, i.e., by a factor

$$f = \frac{g \ 40 + 100}{g \ 40}, \quad (5)$$

and in the process “dilutes” the peak resonance cross section by $1/f$ to

$$\delta\sigma|_{\Theta^+\text{res}} = \frac{37}{1 + 2.5/g} \text{ mb} \quad (6)$$

A careful examination of the total K^+d cross section plots reveals that in the 200 MeV interval of lab momenta 0.5 - 0.7 GeV/c which corresponds to $W=1.5\text{-}1.6$ GeV there are intriguing fluctuations in all experiments! These $\delta\sigma_{K^+d} = 2 - 4$ mb fluctuations, if confirmed by detailed analysis would constitute independent evidence for $\Theta^+ \simeq (1543)$ MeV. If these fluctuations are indeed due to the Θ^+ resonance we infer from Eq. (6) and the conservative estimate $\delta(\sigma) < 4$ mb, that $g < 0.3$ and

$$\Gamma_{\Theta^+} < 6 \text{ MeV}. \quad (7)$$

The above upper bound on the width of a putative $K^+ - n \ \Theta^+$ resonance relies only on the total Kd cross sections and may be highly conservative. Half the resonant cross section is CEX which dramatically manifests via the pions from the K_S decay, and absorption of \bar{K}^0 's regenerated via the K_L 's. A direct study of the viability of the Θ^+ in the specific experiments used in the PDG is beyond the scope of this paper. It may imply even smaller Γ_{Θ^+} , or, more dramatically, verify the existence of the Θ^+ !

III. CAN WE HAVE A NARROW Θ^+ ?

Is our upper bound $\Gamma_{\Theta^+} < 6$ MeV consistent with $I_{\Theta^+} = 0$? CPR suggested $I_{\Theta^+} = 2$ since they expected an unsuppressed “fall-apart” width of Θ^+ of several hundred MeV. Let's

compare Γ_Δ , the widths of the $(3, 3)$ 1230 P-wave pion -nucleon resonance with $p(3, 3) = 0.27$ GeV/c and that of the P-wave Θ^+ with a cm frame momentum $p' = .23$ GeV/c with a $\sim 40\%$ stronger centrifugal barrier suppression of the decay rate. The decay of the Δ but not that of Θ^+ requires creating an extra light $d\bar{d}$ quark pair whereas any break-up of $uudd\bar{s}$, into $\bar{s}u + udd = K^+n$ or $\bar{s}d + duu = K^0p$ is allowed. In the $1/N_c$ expansion[14] or other non-perturbative frameworks[15]- this should suppress the Δ width relative to that of Θ^+ , suggesting

$$\Gamma_{\Theta^+} > .6 \Gamma_{\Delta(3/2,3/2)} = 70 \text{ MeV} , \quad (8)$$

apparently excluding $I(\Theta^+) = 0$.

CPR suggest that the widths of *all* the anti-decuplet states of DPP are larger than the DPP estimates. We note, however, the remarkable internal consistency of the DPP scheme. Thus, following DPP, let $N(1710)$, $J^P = \frac{1}{2}^+$ be the $I = 1/2$ member of $\bar{\mathbf{10}}$, e.g.,

$$N^+ = \frac{2}{\sqrt{3}} \bar{s}s u u d + \frac{1}{\sqrt{3}} \bar{d} d u u d . \quad (9)$$

It has a relatively PDG small width $\Gamma_{N(1710)} = 100$ MeV with only 10-20 MeV partial decay width into the $N\pi$ channel. If indeed the $N(1710)$ and the Θ^+ have similar dynamics then $\Gamma_{N(1710) \rightarrow N\pi} = 10 - 20$ MeV implies, as we shall shortly explain, $\Gamma_{\Theta^+ \rightarrow KN} = 3 - 6$ MeV, which is consistent even with the more stringent upper bound that we inferred from the absence of prominent bumps in the K^+d data.

The probability that the $N(1710)$ does not contain any $s\bar{s}$ and can decay without ‘‘Zweig-Rule’’ violation into a non-strange $N\pi$ final state is only 1/3. Along with the centrifugal barriers ratio, this yields the above estimate for Γ_{Θ^+} .

IV. WHY A LOW-LYING Θ^+ IS LIKELY TO HAVE $I=0$?

If further analysis along the lines of sec II above will imply a Θ^+ much smaller width than the present 6 MeV upper bound, then $I(\Theta^+) = 2$ may be imperative. The following explains why a low lying isotensor state is (theoretically) unlikely:

Let us first present the argument at the hadronic level. The lowest hadronic channel accommodating an isotensor Θ^+ is $\Delta(0)K^+$ with a threshold of $1230 + 495 = 1735$ MeV ~ 300 MeV higher than the KN channel in which the $I = 0$ (and $I = 1$) states can appear. In general channels with lower I spins have stronger binding. Thus in the $\bar{K}N$ channel, the

$I = 0, 1$ Λ and Σ are the lowest $J^P = \frac{1}{2}^+$ bound states with $\Sigma - \Lambda = 80$ MeV. This can be explained as being due to the exchange of the vector ρ meson. If the latter couples to isospin then the exchange generates in general an interaction potential $V \sim \vec{I}_a \cdot \vec{I}_b$ in a channel a,b. Treating this perturbatively yields, when I_a and I_b add up to a total I a contribution:

$$\delta\rho_{a,b} = c [I(I+1) - I_a(I_a+1) - I_b(I_b+1)] \quad (10)$$

Comparing the $I = 2$ and $I = 1$ $\Delta(3/2, 3/2)K$ state and in turn the $I = 1$ and $I = 0$ NK states and assuming for simplicity that the same factor c appears in both, and also in the $\bar{K}N$ channels we find that a putative isotensor Θ^+ will be less bound than the $I=0$ Θ^+ by 200 MeV. The isotensor Θ^+ in the ΔK channel is thus expected to be 500 MeV heavier than the corresponding $I = 0$ KN state!

The pattern of binding in hadronic channels via OBE (One boson exchange) potentials can often be related to the underlying quark structure of the hadrons involved. Thus much of the hard core N-N potential reflecting a repulsive vectorial ω exchange with ω coupling to the total number of light u,d quarks seems to trace back to the Pauli exclusion principle. Also attractive ρ exchange could reflect the possible amelioration of this for smaller numbers of equal flavor light quarks in the two hadrons say in n-p versus nn or pp (which indeed have $I=1$).

Both the solitonic Skyrme picture used by DPP to motivate the Θ^+ , and earlier Bag model calculations suggesting various Hexa-, Penta-, and Tetraquark “exotic” states all treat the system as a “single bag” or a “single, connected color network” rather than as two separate color singlet hadrons.

In a Naive Quark Model the non-exotic qqq baryons and $q\bar{q}$ mesons are viewed as bound states of mildly relativistic “constituent quarks”. The latter “quasi-particles ” are made of bare quarks with the relevant flavor and gluon+ $q\bar{q}$ clouds, have effective masses $m_u \sim m_d \sim 350$ MeV and $m_s \sim 450$ -500 MeV. Once quark confinement is imposed via the “Bag”, or, via confining potentials, the most important “residual” force between the (constituent) quarks is the “hyperfine” chromomagnetic interaction contributing

$$\Delta M = C \sum_{i,j} \frac{1}{m_i m_j} (\vec{S}_i \cdot \vec{S}_j) (\vec{\lambda}_i \cdot \vec{\lambda}_j) \quad (11)$$

with C setting the overall scale of the interaction matrix element, \vec{S}_i , $\vec{\lambda}_i$, and m_i being the spin, color matrix and mass of the quark (or anti-quark) q_i . With hadron-independent C this

explains the observed pattern: $\rho - \pi = 650$ MeV approximately equal to twice $\Delta - N \simeq 300$ MeV, and approximately equal to three halves of $K^* - K = 400$ MeV, which is equal to twice $\Sigma(1380) - \Sigma = 200$ MeV. This is due to

$$\langle \vec{\lambda}_i \cdot \vec{\lambda}_j \rangle_{\text{Baryon}} = \frac{1}{2} \langle \vec{\lambda}_i \cdot \vec{\lambda}_j \rangle_{\text{Meson}} \quad (12)$$

since in the baryon each di-quark pair is, by overall color neutrality, in a $\bar{\mathbf{3}}$ SU(3) color representation whereas the $\mathbf{3}$ and $\bar{\mathbf{3}}$ in the meson add up to a singlet. In addition, we have the inverse mass factors

$$\frac{1}{m_s m_q} \sim \left(\frac{2}{3}\right) \frac{1}{m_q m_{q'}}. \quad (13)$$

where q, q' refer to the lightest u, d quarks.

The idea that also the pattern of the lowest-lying multi-quark states can be inferred by minimizing the overall hyperfine interaction energy has been suggested early on (in a bag model context), by R. Jaffe[16] and developed by several authors [9, 10]. It suggested that the low-lying $0^+ K \bar{K}$ threshold states with $I = 0$ and $I = 1$, namely $f(980)$ and $a(980)$ respectively, are such $s\bar{s}q\bar{q}$ states. Many other four- and five-quark states and in particular the new BaBar $D[s](2317)$ state could have a similar origin [17, 18].

Jaffe further suggested [8] that the di-baryon $H = uuddss$ lowest lying O^+ state is particularly strongly bound: $m_H < 2m_\Lambda$ and the H decays only via repeated weak interactions. While dedicated searches did not find a stable H , stronger binding in these flavor and quantum numbers is likely. Later on, similar considerations suggested that a stable $\bar{c}suud$ pentaquark is even more likely.

The remarkable success of the NQM or bag models is from the point of view of a QCD purist, rather surprising. Equally surprising is the fact that the Skyrme model originally embedded in the large N_c Chiral SU(2) and extended to SU(3) [6] reproduces the same pattern of octet and decuplet ground state baryons and [19] even indicates the special H state in the di-baryon extension of the Skyrme model. This remarkable feature persists also for the new $uudd\bar{s}$ state in the anti-decuplet that DPP derive as the next Skyrme model level. The following brief discussion qualitatively motivates the above statement.

To see most clearly the physics involved consider first an idealized setting where the “heavy” \bar{s} in Θ^+ is replaced by a much heavier \bar{Q} . The heavy (anti-) quark “sits” at the origin serving as a static $\bar{\mathbf{3}}$ SU(3) color source[20] and the H.F $\bar{Q} - q_i$ interactions which are proportional to $1/m(Q)$ can be neglected. The invariance under overall rotations of the

light quark system with respect to the heavy quark “anchoring point” implies a vanishing relative angular momentum $L(qqqq, \bar{Q}) = 0$.

The J^P and isospin of the lowest $\bar{Q}u_1u_2d_1d_2$ state are fixed by minimizing the total energy of the $qqqq$ system, which we assume is dominated by the chromomagnetic H.F Interaction of Eq. (11). Color neutrality of the pentaquark implies that $qqqq$ is in the fundamental $\mathbf{3}$ representation: $\lambda_{u_1} + \lambda_{u_2} + \lambda_{d_1} + \lambda_{d_2} = \mathbf{3}$ and we have anti-symmetry under the joint exchange of the color, spin, flavor and orbital parameters of any q_i and q_j .

For a first, heuristic, go-around we make use of the diquark concept. Any xud system like Λ_s/Σ_s , Λ_c/Σ_c , etc. contains a diquark made of the light ud system with overall $\bar{\mathbf{3}}$ color. The H.F interaction makes the $I = 0, S = 0$ ud and corresponding Λ 's - more tightly bound than the $I = 1$ ud and corresponding Σ 's. The effect is stronger for higher $m(x)$ and weaker xq H.F interactions (the latter prefer triplet ud so that x can anti-align with both u and d). By extrapolating from the s - c quarks we expect $m(ud, S = 1, I = 1) - m(ud, S = 0, I = 0) \sim 200$ MeV. Since the colors of the two quarks have to add up to a $\bar{\mathbf{3}}$ the ud system is anti-symmetric in color and hence, by overall Fermi statistics we have the $I = S$ “locking” for the S-wave quarks.

Consider then a particular pair of ud diquarks, say u_1d_1 in $\bar{\mathbf{3}}$ of color and u_2d_2 in a $\bar{\mathbf{3}}$ of color. The overall $qqqq$ system will be lighter by 400 MeV(!), if both diquarks are in the $I = 0$, so that $I(qqqq) = I(\Theta^+) = 0$ as compared with the case when both diquarks are in $I = 1$ and $I(qqqq) = I(\Theta^+) = 2$. In the energetically-favored case we also have vanishing total spin: $S(qqqq) = 0$. An overall $I = S = 0$ $qqqq$ system is consistent with having the lower lying configuration in the other pairing: $I(u_1d_2) = S(u_1d_2) = I(u_2d_1) = S(u_2d_1) = 0$ as well.

The two $I = S = 0$ diquarks are effectively identical bosons and the wave-function should be symmetric under the exchange of the diquarks. However the color coupling of the two $\bar{\mathbf{3}}$'s of the two diquarks must be anti-symmetric to ensure that $qqqq$ be in the fundamental $\mathbf{3}$ representation of color. Hence, the two diquarks must be in a relative orbital angular momentum $l = 1$ and hence $j(qqqq) = 1$. Upon adding this to $s(\bar{Q}) = 1/2$ the total $J = J(\Theta^+) = 1/2$ is favored by the L-S coupling. Also the parity of the system will be positive on account of the intrinsic negative parity of the \bar{Q} .

The above NQM finger-counting/hand-waving is admittedly crude. We need to allow the q_iq_j pairs to couple also to color sextets, and for $\bar{Q} = \bar{s}$ to carefully consider the H.F

interactions of the \bar{s} as well. Indeed, these extra H.F. interactions may modify the energetics. Yet these considerations exclude the $I = 2$ assignment and select precisely the DPP Θ^+ state, which emerged there in the framework of the SU(3) extended Skyrme model! We cannot predict m_{Θ^+} but neither can DPP without “anchoring” to the $N(1710)$.

V. SUMMARY AND CONCLUSIONS

In this note we have greatly praised the DPP paper and tried to reproduce its predicted $I = 0$, $J^P = \frac{1}{2}^+ \Theta^+$ using simpler arguments. We also noted some curious and extremely intriguing fluctuations in the K^+ -deuteron total cross section data compiled in the PDG as a function of the K^+ lab momenta precisely in those bins where the Fermi-motion broadened Θ^+ state is expected to show up. These could clearly establish the existence of Θ^+ if indeed confirmed by a more careful analysis of the specific experiments included in the PDG compilation. This is particularly so since the large CEX cross section at resonance can manifest in Bubble chambers as quickly decaying K_S 's. The same experiments could, however, “bury” the whole notion of the $I = 0$ resonance if the Γ_{Θ^+} inferred turns out to be too small. In this context we would like to add one final remark.

The color flux diagrams for the $\bar{c}s u u d$ pentaquark depicted in Fig 21. (a) of the review paper on QCD inequalities[21] can be viewed as merely mnemonics for the color couplings with each junction point of three fluxes indicating the corresponding $\epsilon_{a,b,c}$ anti-symmetric color coupling of the three $\mathbf{3}$ or $\bar{\mathbf{3}}$ representations to a color singlet. However, this figure may represent a true configuration-space picture of the pentaquark. In a strong coupling regime, we may wish to consider the flux lines as actual semiclassical configurations of flux tubes existing in configuration space. It is conceivable then that some tunnelling barrier separates the Θ^+ and the lower energy $K^+ n$ baryon and meson state obtained by annihilation (i.e., contraction of two ϵ - symbols) of a junction and an anti-junction. In this case narrow widths could still ensue, though it is not clear how narrow.

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